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# Broad Perspectives in Radar for Ocean Measurements

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National Aeronautics and  
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# **Broad Perspectives in Radar for Ocean Measurements**

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National Aeronautics and  
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ABSTRACT

We evaluate the various active radar implementation options available for the measurement functions of interest for the SEASAT follow-on missions. These functions include surface feature imaging, surface pressure and vertical profile, atmospheric sounding, surface backscatter and wind speed determination, surface current location, wavelength spectra, sea surface topography, and ice/snow thickness. We then examine some concepts for the Synthetic Aperture Imaging Radar that may be useful in the design and selection of the implementation options for these missions. In this evaluation the applicability of these instruments for the VOIR mission is also kept under consideration.

## I. INTRODUCTION

Due to cloud cover over the ocean's surface, radar techniques are most practical for the observation and monitoring of the ocean conditions by satellite. This study, sponsored by the Technology Planning Office at NASA Headquarters, identifies the available radar concepts to provide the measurement functions of interest to the oceanographic user community and briefly describes the future studies that would be desirable to fully exploit the potential of these radar techniques.

The functions of interest for measurement are surface feature imaging, surface pressure and vertical profile, atmospheric sounding, surface backscatter and wind speed determination, surface current location, wavelength spectra, sea surface topography (geoids, tides and current bumps), ice/snow thickness, surface roughness and coastal bathymetry. The present study is intended to identify the active radar implementation options that are currently available to perform these measurement functions, suggest criteria for choice of the particular instruments to fulfill the requirements of the SEASAT-FOLLOW-ON missions and point out necessary studies and developments that need to be undertaken to improve the effectiveness of these instruments. In this study we also evaluate some concepts for the Synthetic Aperture Imaging Radar that may be of interest in the design of the SEASAT-FOLLOW-ON implementation options.

We find that, while the implementation options are in principle available to perform the measurement functions described, further work is necessary to develop and understand these instruments for spacecraft applications. Of

particular interest for future development is the checkerboard Synthetic Aperture Imaging Radar (which images different range intervals for successive azimuth strips to produce a checker type image) to provide high swath widths for global oceanography, use of the Synthetic Aperture Radar as an altimeter or scatterometer, a combined scatterometer-atmospheric sounder, a microwave sounder for surface pressure measurements, and a real-time low cost, onboard processor for Synthetic Aperture Radar Data. The application of some of these instruments for a Venus Orbital Imaging Radar (VOIR) mission is briefly discussed throughout this report.

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## II. SEASAT-FOLLOW-ON MEASUREMENT FUNCTIONS - IMPLEMENTATION OPTIONS

The primary measurement functions of interest for the SEASAT-FOLLOW-ON Missions are surface feature imaging, surface pressure and vertical profile, atmospheric sounding, surface backscatter and wind speed determination, surface current location, wavelength spectra, sea surface topography (geoids, tides and current bumps), ice/snow thickness, surface roughness and coastal bathymetry. In this section we determine some of the active radar implementation options available to perform these measurement functions, examine their current state and possible future development, and propose future studies for developing these options.

While imaging can be performed by the Synthetic Aperture Radar or a real aperture radar, only the Synthetic Aperture Radar is practical for spacecraft purposes. High resolution in the cross-track dimension, in this system, is obtained by a short or wide bandwidth chirp pulse and by processing the return signal as a function of time, the time delay between the transmission and reception being proportional to the distance between the radar and the target. In the along-track dimension, high resolution is obtained by measuring the Doppler frequency shift of the return signal as the radar platform flies past the target and match filtering this return to provide the desired resolution. While the theoretical along-track resolution is equal to half the antenna length the cross-track resolution is half the radar pulse length.

In the design of this radar system, certain fundamental constraints must be recognized. The time between successive pulses determines the maximum range that can be mapped by the radar system. On the other hand, too low a pulse repetition frequency results in azimuth ambiguities due to Doppler foldover.

As a result, the unambiguous range that can be mapped is approximately  $cD/8v$  where  $c$  is the velocity of light,  $D$  the azimuth dimension of the antenna, and  $v$  the spacecraft velocity. Since the along-track resolution of the radar system is  $D/2$ , there is a swath width along-track resolution limitation where the ratio of the maximum range to the along-track resolution has to be less than  $c/4v$ . Since the change in range as a target crosses the beam should be less than half a pulse length, the product of the square of the along-track resolution and the cross-track resolution is required to be greater than the  $H\lambda^2/16$  where  $H$  is the altitude of the radar platform and the radar wavelength. This sets a limit to the best resolution attainable in terms of the spacecraft altitude and radar wavelength.

The capability of the Synthetic Aperture Radar to image various oceanographic and geologic features of interest has been well-demonstrated in a number of aircraft flights<sup>1-6</sup>. Various studies have also been made attempting to connect the properties of the radar image to the surface being imaged<sup>7-11</sup>, however, much experimental and theoretical work still needs to be done in order to develop a complete understanding of the electromagnetic scattering and the radar imaging processes, and thus enable one to effectively extract the information available in a radar image.

Since the Synthetic Aperture Radar contains all the components for an altimeter or a scatterometer, it may be used as either of these instruments. For operation as an altimeter, the radar system would need to incorporate a nadir lobe in its antenna pattern and its pulse length capability governed by the specifications of the altimeter. As a scatterometer, the only requirement would be an effective calibration of the radar system. In both applications,



it would not be necessary to perform the compression at the along-track radar return. Also many novel modifications may be developed to the Synthetic Aperture Radar, such as the multibeam-multifrequency or the scanning checkerboard radar system to overcome the swath-width, along-track resolution limitation. The spinning spacecraft SAR where the rotation of the spacecraft is used to develop the Synthetic Aperture is also of interest.

While both X- and L-band are practical for the Earth-based SEASAT mission, it is desirable to restrain the wavelengths for the VOIR Mission to be greater than S-band due to the absorption of the Venus atmosphere. The Synthetic Aperture Radar is the only practical instrument capable of providing high resolution imagery on both the SEASAT and the VOIR missions due to the cloud cover over parts of the oceans and the opacity of the Venus atmosphere to other electromagnetic frequencies.

The surface pressure may, in principle, be determined by the microwave pressure sounder which is a radar system operating in the 50 GHz region, and the vertical pressure profile determined from this value by using the hydrostatic approximation in conjunction with the measured temperature field. The microwave pressure sounder is based on the dependence of the absorption of microwave energy by the oxygen content in the atmosphere on pressure. Simultaneous operation at six frequencies: 26.2, 33.28, 40.65, 52.87, 67.45, and 72.61 GHz, has been proposed; and, by comparing their absorption with existing data, the surface pressure may be deduced. However, this instrument concept is only in the theoretical stage and considerable work needs to be done to verify, both theoretically and experimentally, the essential features of this device and demonstrate its feasibility for spacecraft applications. In the application of this instrument concept for the VOIR mission, the absorption by oxygen may not be useable and further study is required to establish its feasibility.

While it has been shown that, by using microwave frequencies comparable to the sizes of the precipitation particles and by measuring the Doppler shifts of the returns from these particles, both the mapping and measurement of precipitation rates may be performed, the principal problem in designing an atmospheric sounder is in providing a narrow enough beam at near Earth altitudes so that returns at different heights but the same range distance may be differentiated. This requires the use of a large x-band antenna, approximately 7.5 m in diameter, the antenna beam being operated in a coherent or non-coherent mode for the simple precipitation mapping mode and coherently for determining the velocity field of the precipitation from the Doppler shift of the return. The design, operation and demonstration of such an atmospheric sounder still needs to be done.

The wind speed may be determined by the scatterometer. This is a simple radar system operating at X-band and measures the scattering cross-section as a function of angle (by scanning) of the ocean surface. The ocean cross-section, dependent upon the scattering of microwaves from the capillary and small gravity waves, is known to be related to wind speed<sup>12</sup>. Thus, the scatterometer can be used for the wind speed measurements. It may be noted that the Synthetic Aperture Radar may also be used as a scatterometer. In general, it is desirable to have four orthogonally pointed radar beams so that the wind direction information may also be obtained<sup>13</sup>.

The wavelength spectra of ocean waves may be determined in a number of ways. By Fourier transforming the ocean wave imagery obtained by the Synthetic Aperture Radar, the wavelength spectra may be inferred. However, considerable work needs to be performed before the precise relationship between the SAR image transforms and the wavelength spectra is determined<sup>14</sup>.

The two-frequency radar may also be used to determine wave spectra, where, by examining the power spectrum of the product of returns as a function of the frequency separation the wavelength of the ocean wave may be deduced<sup>15</sup>.

A short pulse radar may be used to determine the ocean wavelength spectra from a short pulse spectrometer<sup>16</sup>. Also, since the Synthetic Aperture Radar has the essential components of the two-frequency radar or the short pulse spectrometer, it may be used in that mode. Alternatively the ocean wave spectrum could possibly be extracted directly from the Synthetic Aperture Radar signal data. However, this would require considerable future work.

The sea surface topography may be determined with an altimeter. High resolution may be obtained by using a very short pulse and thus determining the altitude accurately. Using information on the orbital parameters of the radar platform, the sea surface topography may be inferred. Again, the X-band SAR may be used as an altimeter if it has a nadir lobe and the capability of a very short pulse of the desired resolution.

Ice/snow thickness, surface roughness and coastal bathymetry may again be determined by the imaging radar. However, it is desirable to consider the development of multispectral radar systems to differentiate in ambiguities arising from different ice types, snow and water surfaces.

A summary of the various implementation options available to perform the desired measurement functions is given in Table I. In determining the most reasonable choice of the implementation options the following criteria must be considered:

1. Provide swath width coverage for global oceanography (1500 km), and improve resolution for accurate feature identification and wave forecasting (10 m).
2. Provide new measurement functions to extend Seasat-A capability. These are Vertical Pressure Sounding and Atmospheric Sounding. The implementation options for these measurement functions still need to be developed.
3. Improve the current capability for data handling and processing so that the necessary quantities of interest may be supplied to users on a real-time basis.
4. Integration of the various implementation options selected to lower cost, requirements on spacecraft such as power and weight, and improve accuracy and reliability.

Based on the criteria and the limitations described, the design and characteristics of the following options need further investigation as possible options for SEASAT-FOLLOW-ON:

1. Use of a multibeam Synthetic Aperture Radar which is capable of operating in the "checker" mode (10 km x 10 km strips all the way to the horizon) or providing continuous coverage to 1500 km (L or X-band). For the X-band radar, a high bandwidth capability and nadir lobe to be used for altimetry (sea surface topography).



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MEASUREMENT FUNCTION	IMPLEMENTATION OPTIONS	SPACE RADAR PARAMETERS				LIMITING FACTORS			OTHER REQUIREMENTS	
		WAVELENGTH	ANT. ILLUM.	PULSE FORM & RATE	ONBOARD PROCESSING	RESOLUTION	RANGE	SWATH WIDTH	DYNAMIC RANGE	POLARIZATION
1. IMAGING	SYNTHETIC APERTURE RADAR	L OR X	6.2 deg RANGE, 1 deg AZIMUTH 20 deg LOOK ANGLE	33.4 $\mu$ sec 19 MHz BW 1645 PRF at L-BAND	NONE, FURTHER WORK NEEDED	$X^2 \text{ RES}^2 \text{ RES}^2 \geq \frac{H_a^2}{16}$ L-BAND = 13 m X-BAND = 3 m AT 800 km ORBIT	20 dB REFLECTIVITY VARIATION	100 km	20 dB	DUAL
	SAR (MULTIBEAM, MULTIFREQUENCY)	L OR X	MULTIPLE BEAMS TO 60° IN RANGE, WIDTH OF BEAMS VARIABLE	33.4 $\mu$ sec 19 MHz BW 1645 PRF AT L-BAND	FURTHER WORK NEEDED	$X^2 \text{ RES}^2 \text{ RES}^2 \geq \frac{H_a^2}{8}$	20 dB/BEAM REFLECTIVITY VARIATION	1500 km	100 dB	DUAL
	SPINNING SPACECRAFT SCANNING BEAM SAR	L OR X				CAN BE OPERATED ONLY ON LOW RESOLUTION MODE DUE TO PRF- AZIMUTH AMBIGUITY CONSTRAINTS	20 dB REFLECTIVITY VARIATION	HIGH SWATH → LOW RESOLUTION		
2. SURFACE PRESSURE & VERTICAL PROFILE	MICROWAVE PRESSURE SOUNDER (6 FREQUENCY)	26.2 GHz 33.28 40.65 52.87 67.45 72.61	1° BEAM WIDTH	PULSED CW	YES	3 mb (1 mb POSSIBLE) 50 km SPATIAL RESOLUTION	900 - 1000 mb	NADIR LOOK (LARGER SWATH POSSIBLE WITH SCANNING MODE)	30 dB	SINGLE
	DOWNWARD LOOKING SCANNING PENCIL BEAM RADAR	12 GHz X-BAND	0.2 deg. 45 deg ANGLE SCANNING, ANT SIZE 7.5 m DIAM	2 $\mu$ sec 2300 PPS	YES	2 mm/hr 1.5 km RESOLUTION	2 mm/hr MINIMUM RAIN INTENSITY	800 km	20 dB	DUAL
3. ATMOSPHERIC SOUNDING	MULTIBEAM DOPPLER SYSTEM	12 GHz X-BAND	0.2 deg. 20 - 60 deg SCAN, 7.5 m DIAM	10 $\mu$ sec 2.5 KHz	YES	2 m/sec, VERT RESOLUTION 1.5 km	> 35 m/sec	1500 km	20 dB	SINGLE
	SCATTEROMETER	14.6 GHz	1.5° BEAM WIDTH, 0 TO 59° SCAN 4 ANTENNAS	PULSED CW 40 PPS	YES	50 km ERRORS $\pm 2$ m/sec OR $\pm 10\%$ , $\pm 20^\circ$	3 TO 25 m/sec 0 TO 360°	900 km	80 dB	DUAL
4. SURFACE BACKSCATTER VARIATION & WIND SPEED DETERMINATION	SYNTHETIC APERTURE RADAR (FORWARD, BACKWARD LOOKING) (MULTIBEAM OR SINGLE)	X-BAND	AS IN IMAGING APPLICATION				20 dB/BEAM BACKSCATTER VARIATION	100 km TO SINGLE BEAM 1500 km MULTIPLE BEAMS	20 dB PER BEAM	DUAL
	SYNTHETIC APERTURE RADAR (SINGLE OR MULTIPLE BEAM)	AS IN IMAGING APPLICATION X-BAND OR L-BAND				WILL DETECT SURFACE CURRENTS 90% OF THE TIME, VELOCITY EFFECTS OF CURRENT TOO SMALL FOR DETECTION				
6. WAVELENGTH SPECTRA	SYNTHETIC APERTURE RADAR (SINGLE BEAM OR MULTIBEAM IMAGES)	X-BAND OR L-BAND	AS IN IMAGING APPLICATION		FURTHER WORK NEEDED		MIN 50 m WAVES L-BAND 10 m X-BAND			
	TWO FREQUENCY RADAR	9.3 GHz $\pm 75$ MHz 2nd FREQ VARIATION	6 deg BEAM WIDTH 15° LOW ANGLE	CW	YES	FURTHER WORK NECESSARY				SINGLE
	SHORT PULSE SPECTROMETER	X-BAND	6 deg BEAM WIDTH	0.04 $\mu$ sec	YES					DUAL
	SYNTHETIC APERTURE RADAR (SIGNAL DATA)	X OR L BAND	AS IN IMAGING APPLICATION, USE SIGNAL IN THE SHORT PULSE OR TWO FREQUENCY RADAR MODE							
7. SEA SURFACE TOPOGRAPHY GEO- IDS, TIDES, CURRENT BUMPS)	ALTIMETER	13.5 GHz $\pm 160$ MHz	NADIR ILLUMINATION	1500 PPS 3.2 $\mu$ sec CHIRP	YES	2 x 7 km SPOT $\pm 7$ cm ERROR	7 cm HEIGHT VARIATION 10m ABSOLUTE ALTITUDE	18 km ALONG EQUATOR		SINGLE
	SYNTHETIC APERTURE RADAR (WITH LARGE BANDWIDTH CAPABILITY), NADIR LOBE	X-BAND	NADIR LOBE	LARGE BW PULSES	YES	3 x 3 km SPOT				
8. ICE, SNOW THICK- NESS, SURFACE ROUGHNESS, COAST- AL BATHYMETRY	SYNTHETIC APERTURE RADAR (SINGLE BEAM, MULTIPLE BEAM)	X OR L-BAND VHF	AS IN IMAGING APPLICATION			L, X BAND FOR ROUGHNESS VHF FOR SOUNDING APPLICATIONS	20 dB SCATTERING VARIATION	100 km SINGLE BEAM TO 1500 km MULTIPLE BEAMS		DUAL

TABLE I

## SEASAT FOLLOW-ON Implementation Options

		OTHER REQUIREMENTS		RADAR CHARACTERISTICS				SPACECRAFT REQUIREMENTS	DEVELOPMENT STATUS	COMMONALITIES EARTH + VENUS	USER REQUIREMENTS
SWATH WIDTH	DYNAMIC RANGE	POLARIZATION	MASS kg	POWER	DATA RATE	SIZE					
10 km	20 dB	DUAL	75 + ANTENNAS	800 watts X-BAND 500 watts L-BAND	110 MEGA BITS	NEED STUDY	CALCULATIONS AT 800 km ORBIT	AIRCRAFT TESTS L-BAND ON SEASAT-A	L-BAND S-BAND	25 m RESOLUTION, DESIRE TOWARDS 10 m 100 km SWATH WIDTH DESIRE TOWARDS 100 km DYNAMIC RANGE 0 TO 100 dB	
10 km	100 dB	DUAL	FURTHER STUDY NECESSARY		SEE TABLE II			NONE			
HIGH SWATH LOW RESOLUTION								NONE			
LOOK-ALONG SWATH (SINGLE MODE)	30 dB	SINGLE	100 kg	6 watts OUTPUT POWER	8 kb/sec		NONE	THEORETICAL FEASIBILITY ESTABLISHED, FURTHER WORK NEEDED	MAY NEED DIFFERENT FREQUENCIES SIMILAR SYSTEM, (NEED STUDY)	ACCURACY <1 m, RESOLUTION 50 km NOMINAL DESIRE TOWARDS 5 km, SWATH NADIR TO 1500 km	
10 km	20 dB	DUAL		3.5 kw PEAK 16 watts AVE POWER	2 kb/sec		CALCULATIONS AT 400 km ORBIT CAN USE SPACECRAFT SPIN FOR SCAN	NONE	WILL WORK ON VENUS X OR S	ACCURACY 0.1 cm/cm <sup>2</sup> CONTENT, 0.5 cm/hr RAIN RATE, 1 m/sec PARTICLE VELOCITY, RESOLUTION 50 km to 5 km DESIRE, SWATH 1500 km	
10 km	20 dB	SINGLE		5 kw PEAK 100 watts AVE POWER		400 km ORBIT CAN USE SPACECRAFT SPIN FOR SCAN	NONE				
10 km	80 dB	DUAL	135 kg	200 watts	2 kb/sec		SEASAT ORBIT 800 km	AIRCRAFT TESTS SEASAT-A	S-BAND ON VENUS	<1 dB NOMINAL, <0.5 dB DESIRE, RES. 50 km MIN TO 5 km DESIRE, SWATH 1500 km, WIND 1 m/sec AND 10° TO 0-5 m/sec and 2°	
10 m TO SINGLE BEAM 10 km MULTIPLE BEAMS	20 dB PER BEAM		75 + ANTENNAS	500 watts L-BAND SINGLE BEAM	110 mega bits			REQUIRE OPERATION OF SAR AS SCATTEROMETER			
		SINGLE	NEED STUDY		8 kb/sec			AIRCRAFT OBSERVATIONS SEASAT-A	X-BAND L-BAND	30 cm/sec NOMINAL TO 3 cm/sec 10° RESOLUTION 1 km NOMINAL TO 10 m DESIRE SWATH 100 TO 1500 km	
								AIRCRAFT TESTS SEASAT-A			
		DUAL	70 kg	200 w	8 kb/sec			TOWER EXPTS COMPLETED		50 m, 10° DESIRE TOWARDS 10 m, 5 TO 10°, 10 km SAMPLES ON 100 km CENTERS TO HORIZON, DYNAMIC RANGE LOW TO BOUND WAVES	
			75 + ANTENNAS	500 watts L-BAND SINGLE BEAM	8 kb/sec			NONE			
10 km EQUATOR		SINGLE	70 kg	200 w	8 kb/sec		AT 800 km ORBIT	AIRCRAFT TESTS SEASAT-A	S-BAND ON VENUS	10 cm NOMINAL TO 1 TO 2 cm DESIRE, SWATH NADIR	
			75 + ANTENNAS	200 w	110 mega bits			NONE			
10 km SINGLE BEAM 10 km MULTIPLE BEAMS		DUAL		500 w L-BAND SINGLE BEAM				AIRCRAFT OBSERVATIONS SEASAT-A	X, L, VHF	0 TO 30 m NOMINAL, 100 m DESIRE, VERTICAL RESOLUTION 0.5 m NOMINAL TO 15 cm DESIRE, HORIZONTAL RESOLUTION 2 km NOMINAL TO 50 m DESIRE, SWATH NADIR TO 1500 km DESIRE	



2. Use of the scatterometer with a narrow beam and Doppler processing capability to provide simultaneous atmospheric sounding. Since the total width of the beam on the earth's surface is the product of the wavelength, orbit altitude and the inverse of the antenna diameter, the narrow beam would require a low altitude spacecraft orbit.
3. Design of the microwave pressure sounder for surface pressure and vertical profile measurements.
4. Improvements in real-time data handling capability.

### III. IMAGING RADAR - ADVANCED SYSTEM CONCEPTS

The synthetic aperture radar is a basic instrument for the VOIR and SEASAT Missions, both because of its capability to provide all-weather images and because it can be operated as other radar instruments. It is, therefore, desirable to explore new system concepts that would enable more effective use of this instrument. We look into the design possibilities of a checkerboard radar system that would provide increased swath width while not compromising resolution highly desirable for global oceanography. The forward and backward looking radar systems can be used both for providing different viewing aspects for the same surface and allow possibilities for the radar system to be operated as a scatterometer. It is desirable to investigate the difficulties involved with building an S-band radar system since this allows higher possible resolution at spacecraft altitudes, is not highly affected by the Earth's or Venus' atmosphere, and since there is some question whether L-band radar devices for satellites may be allowed due to international agreements. Finally, we investigate the possible use of the Synthetic Aperture Radar as an altimeter, which would result in considerable saving of cost for future missions.

#### A. CHECKERBOARD IMAGING RADAR

The checkerboard imaging radar is a class of radar systems that would allow imagery for swaths not currently allowed by the conventional spacecraft radar design. High swath widths require low PRF's due to pulse interleaving constraints. Low PRF's result in azimuth ambiguities due to Doppler fold-over. The unambiguous range that can be mapped is approximately  $cD/8v$  where  $c$  is the velocity of light,  $D$  the azimuth dimension of the antenna, and  $v$  the spacecraft velocity. The azimuth resolution of the synthetic aperture system is equal to  $D/2$ , and a high resolution limits the possible swaths available. For Seasat-A parameters and an azimuth antenna dimension of 12 m, the swath width is limited to 100 km. For global oceanography a swath width of 1500 km is desired with 10 x 10 m resolution. Continuous swaths are not necessary, however, since the spectra of ocean waves change slowly and 10 x 10 km swaths centered at 100 km intervals are acceptable. The image of the ocean may therefore be obtained in a repeating pattern of strips, each strip being centered at different ranges. Thus, for example, the radar would first image a 10 km x 10 km strip on nadir, then one centered at 100 km range then at 200 km range up to 1500 km, and then repeat the pattern. However, the 10 km x 10 km strip number is not a limitation and the maximum width of the strip in range, determined by the PRF azimuth ambiguity limitation, can be 100 km centered at 100 km intervals. While with a single beam system, the beam has to be shifted in elevation after each successive azimuth interval to image strips centered at different ranges, a multibeam system may be employed to do simultaneous imaging of the successive strips. Each beam must be separable from the others and this may be done by using different frequencies for

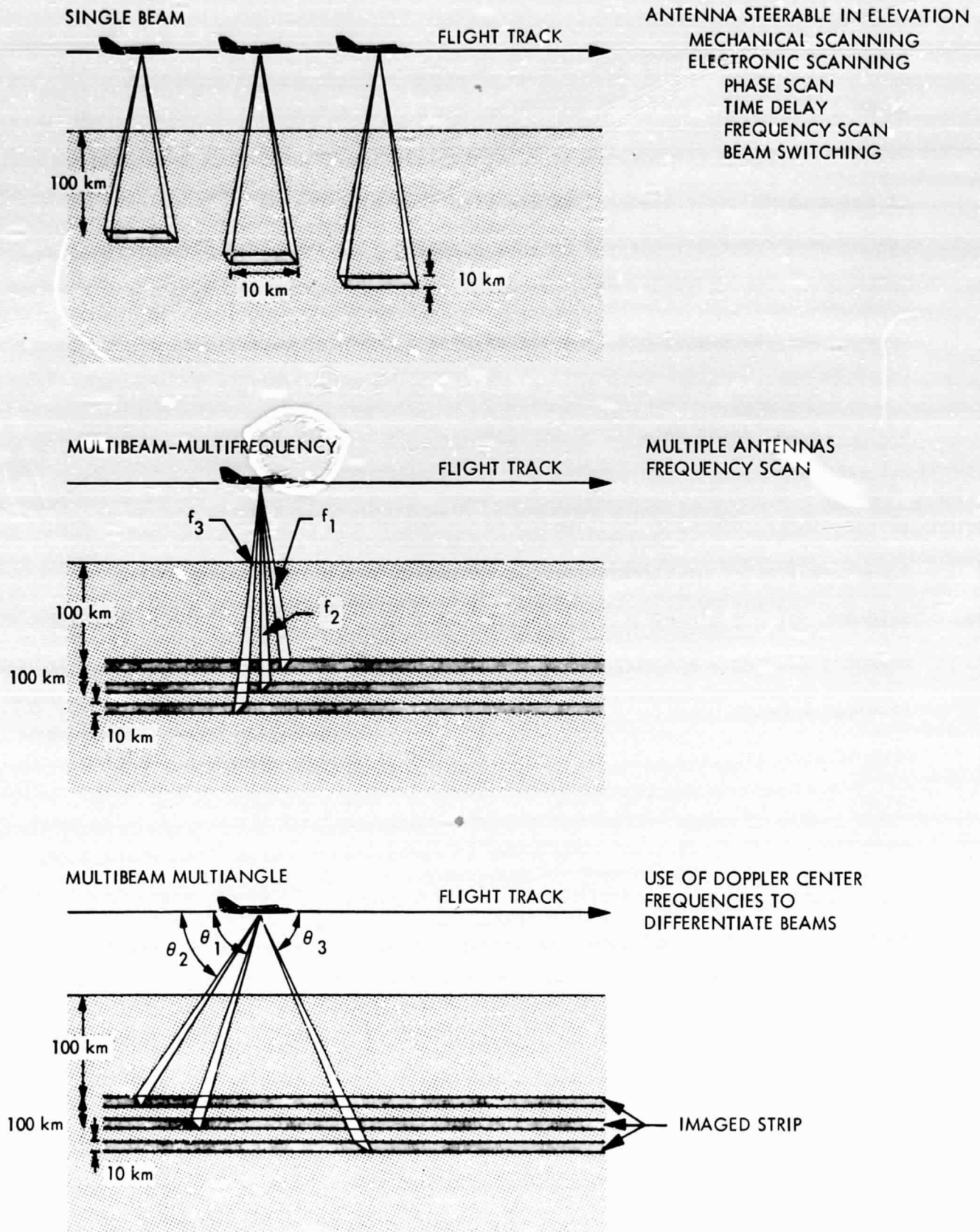


Fig. 1. Multibeam Radar Options

each beam and separating the returns by frequency, or pointing the successive beams at different angles in the direction of the spacecraft flight path and using the doppler frequencies to differentiate the returns from each beam. If beams at multiple frequencies are used then either a multiple antenna system or a frequency scanned antenna operated simultaneously with different frequencies may be used. If the Doppler is to be used to separate returns from successive beams, pointing the antenna forward or backward at angle intervals much greater than the beamwidth should be sufficient to differentiate the different returns on the basis of the Doppler center frequencies.

If the single beam mode is selected to implement the checkerboard radar, different choices are available for the system to be used for scanning the antenna angle in elevation. Mechanical scanning is cheap and simple, but the scanners are heavy and cumbersome for spacecraft. Also, each change in angle involves time to stabilize the antenna at the new position. Electronic scanning is more accurate but costly and requires a complex antenna. The electronic scanning may employ either phase delay, frequency scan or time delay scanning. In phase scanning the array of radiators in the antenna would have their phase shifted to steer the beam. In frequency scanning a frequency dependent delay line is connected between successive radiators so that the beam front angle depends upon frequency. And time-delay scanning involves the use of time delay networks. A beam switching system may be employed where a multiplicity of beams are formed and a single beam is selected through a switching matrix. In the use of frequency scanning, it must be noted that the range imagery utilizes pulse compression and the bandwidth of time chirped pulse will interact with the frequency scanning system. An evaluation of this effect on the imagery is necessary before frequency scanning can be employed



for the checkerboard radar. While phase scanning is also frequency dependent, this effect can be corrected for.

If the SEASAT-A antenna system is used, then images of 100 km swath width centered at 100 km range intervals and having a minimum azimuth dimension of 10 km are produced, for each successive azimuth strip. The antenna size and data rate requirements are the same as for SEASAT-A and the only difference is in the scanning capability of the antenna used and the power required. On the other hand, if only 10 km swaths centered at 10 km range intervals are required, then the elevation dimension of the antenna has to be increased by a factor of 10. Since the smaller swath width allows a higher PRF, the azimuth antenna and the azimuth resolution can be reduced by a factor of 10, the data rate and total antenna area not being changed. However, for this case, the synthetic antenna length is increased by a factor of ten which may be too long an azimuth interval for the checkerboard radar image strips. Also, while in principle this would allow a resolution of 1/2 m in azimuth, this would not be obtainable due to the 13 m resolution limit for the spacecraft being at SEASAT altitudes. This resolution limit is obtained from the relation

$$(\text{azimuth resolution})^2(\text{range resolution}) \leq \frac{H\lambda^2}{16}$$

where H is the spacecraft altitude and  $\lambda$  the operating wavelength. Thus, it may be more useful to employ a 12 m x 12 m square antenna with a 10 km x 10 km footprint, which would require a factor of 10 less power and data rate but may be more difficult to install, or use only 10 km of the available 100 km synthetic aperture for the 12 m antenna. For an X-band checkerboard

radar at SEASAT altitudes, 100 km swaths centered at successive 100 km range intervals for each 10 km azimuth interval, the antenna dimension is a tenth of the L-band dimension in elevation and equal to the L-band dimension in azimuth. For 10 km swaths centered at 100 km ranges, at each 10 km azimuth interval the antenna dimension is approximately 1 x 1 m.

The performance and requirements of the multibeam system are evaluated similarly. The multibeam system is similar to the single beam checkerboard system except, instead of changing the elevation of a single beam antenna at successive azimuth intervals, separate beams are employed to image the swaths at each range interval, this providing continuous coverage for each swath. It is necessary that returns from different beams be separable in the receiver and this may be done by either operating each beam at a different frequency or pointing each beam at a different angle along track so that the center Doppler frequencies for the returns are different.

If multifrequency beams are used, a separate antenna for each beam may be used. For 100 km swath per beam, which would give continuous coverage to 1500 km, the total L-band antenna size would be 15 m in range and 12 m in azimuth, being 1 m in range for each beam. The total power and bit rate would be fifteen times the SEASAT-A single beam configuration. The X-band antenna, on the other hand, would be 1.5 m in range and 12 m in azimuth, the antenna size for each beam being 0.1 m in range and 12 m in azimuth. Again the power and bit rate would be at least fifteen times the requirement for a single beam system.

If 10 km range strips spaced by 100 km are required, each strip would require an antenna 10 m x 12 m if the synthetic aperture length is to be maintained



at 10 km, and the total power and bit rate for 15 beams would be 1-1/2 times that for SEASAT-A. On the other hand, 100 km synthetic aperture length would require the azimuth dimension of each antenna to be only 1.2 m and the total dimension to be 10 x 18 m if the antennas are stacked in the azimuth dimension. The X-band antenna size for the 15 beams would be 1.5 x 10 m for 100 km swaths for antennas stacked in the azimuth direction, where the power and bit rate requirements for the 10 km swaths are equal to the single antenna case.

Alternatively, a single frequency scan antenna may be used, each beam of different frequency designed to point at a different angle. For 10 km swath strips the antenna dimension would then be 10 x 12 m for a 10 km synthetic aperture length, and 10 x 1.2 m for a 100 km synthetic aperture length, and 1 x 12 m for 100 km swath strips, the power and bit rate requirements being the same as for the multiple antenna system. The chief drawback of the frequency scan antenna would be the interaction of the chirp bandwidth with the frequency scan system which needs to be corrected for. Also for each type of multifrequency-beam system, it is necessary for the transmitter to be capable of generating the multiple frequencies and the receiver to detect and record them.

A simpler multibeam system is one using different dopplers to separate the returns from different beams. For a beam pointed at an angle  $\theta$  in the direction of the spacecraft flight track, the return is centered at the Doppler frequency  $f v/c \sin\theta$ , for  $f$  the radar frequency. The beamwidth for the 12 m antenna is 0.01 radian, and returns from beams separated by more than 10 degrees should be easily separable in the receiver. If each beam illuminates a different section of the swath then simultaneous coverage of

different strips can be obtained. Also for 10 km swath strips centered at 100 km range intervals, and a 12 m azimuth antenna dimension, fifteen beams would only require 1.5 times the power and bit rate as the single beam SEASAT-A system and the only requirement difference in the design of the radar system would be in designing an appropriate multibeam antenna and a receiver capable of differentiating the different beam returns on the basis of their Doppler frequencies. A summary of the radar parameters vs. antenna characteristics is given in Table II.

It is necessary to point out that in the radar design, special consideration must be given to the range ambiguity problem. The ocean cross-section depends upon the angle of illumination and the radar receiver. The near range return is higher than the far range return and the return pulse has an apparent shift from the position if the ocean surface cross-section was independent of angle. However, this effect is serious only for elevation angles greater than  $45^\circ$ , and the range ambiguities must be accounted for in the antenna design for higher look angles.

A further consideration in the design of the oceanographic radar system is the effect of the ocean wave motion on the focus of the processing system. If standard processing is employed with no compensation for the ocean wave motion, the effective radar resolution is

$$\left[ \Delta x + \left( \frac{2\lambda H}{\Delta x} \left( \frac{g}{k_{wx}} \right)^{1/2} \right) \right]$$

where  $\Delta x$  is the radar resolution for a stationary target,  $g$  the acceleration due to gravity and  $k_{wx}$  the azimuth component of the ocean-wave-velocity-

TABLE II  
Radar Parameters vs Antenna Characteristics (Approximate Values, SEASAT Parameters)

Frequency	Footprint (Range x Azimuth km)	Azimuth Resolution Available m	Antenna Size (m) (Range x Azimuth)	Data Rate Megabits/Sec.	Power (watts)	PRF
L-Band Single Beam	100 x 10	6	1 x 12	110	500	1645
	10 x 100	0.6	10 x 1.2	110	500	16450
	10 x 10	6	10 x 12	11	50	1645
L-Band, Multi- Frequency Multi-Beam Multi-Antenna	100 x 10 15 antennas	6	15 x 12	1650	7500	1645
	10 x 100 15 antennas	6	10 x 18	1650	7500	16450
L-Band, Multi- Beam, Multi- Angle	10 x 10 15 beams	6	10 x 12	165	750	1645
X-Band Single Beam	100 x 1	6	0.1 x 12	110	1300	1645
	10 x 10	0.6	1 x 1.2	110	1300	16450
	10 x 1	6	1 x 12	11	130	1645
X-Band, Multi- Beam, Multi- Angle	10 x 1	6	1 x 12	165	1950	1645

vector. Optimum processor resolution may however be obtained by adjusting the processor focusing parameter for each  $k_{wx}$ , either by determining this number from other means, or using some iterative technique for the processor autofocus.

#### B. FORWARD AND BACKWARD LOOKING RADARS

The forward and backward looking imaging radars have antenna systems that are pointed in the same or the opposite direction of the radar platform flight line, in addition to being pointed sideways. There do not appear to be any major technological problems for the operation of such a system, however, certain modifications in the radar design need to be accounted for due to the different geometry employed.

The Doppler spectrum is now centered at  $\pm(v/c)f \sin\theta$  where  $f$  is radar frequency,  $v$  the aircraft velocity and  $\theta$  the angle the beam makes from the straight down-mode. The spectrum bandwidth is equal to  $\pm(v/c)f \sin\theta \sin(\Delta\theta)$  for small  $\Delta\theta$  where  $\Delta\theta$  is the azimuth beamwidth. The fact that the Doppler spectrum is not centered at zero must be accounted for either in the radar receiver demodulator or in the optical recorder, since the quantity of interest for recording is  $\pm(v/c)f \sin(\Delta\theta)$  and the film response may not be able to accommodate the nonlinear effects due to the added Doppler component if the radar system is operated in the standard sidelooking mode. In addition the curves of constant range and Doppler look different in the forward or backward looking mode and so the imaging geometry would have some differences from the standard sidelooking mode. The effect of range ambiguity and lower radar cross-sections due to the steeper angles will need to be considered in



the radar system design. The corrections for the earth's rotation and curvature, range migration and antenna pointing error, while not major problems, would have differences from the standard sidelooking mode operation.

### C. S-BAND RADAR

The signal to noise ratio of a radar system is directly proportional to the square of the wavelength, the reflection coefficient of the target area and inversely proportional to the bandwidth employed. On the other hand the reflection coefficient of the target area is inversely proportional to the fourth power of the wavelength used if the Bragg scattering from the same set of wavelets takes place. In the absence of detailed experimental comparisons of the ocean scattering cross-section for S-band vs L-band, it is difficult to arrive at the reflection coefficient on the ocean for S-band, and an accurate determination of the power requirements for the S-band radar. However the effect of increased bandwidth and ocean scattering cross-section may more than compensate for the propagation effects for S-band and the power required may not be more than for an L-band radar.

The azimuth resolution is equal to the azimuth size of the antenna and does not depend upon the wavelength used. The range resolution is determined by the bandwidth used. Since the S-band bandwidth available is likely to be more than for L-band, a higher range resolution is possible in principle. Also, the square of the azimuth resolution produced by the range resolution must be less than  $H\lambda^2/16$  where  $H$  is the spacecraft altitude. The Seasat-A L-band limit of  $18 \times 18$  m would, therefore, be improved at at least a factor of two.

Since the unambiguous range is independent of wavelength, the same PRF-swath width limitations apply for S-band as for L-band. The antenna dimensions must be reduced, proportional to wavelength, in range so that the same area is illuminated for S-band in elevation as for L-band. While there does not appear to be any conceptual difficulty in building an S-band SAR, the availability of a solid-state system or space qualified tube transmitter still needs to be studied. Also, experimental work needs to be done on the radar scattering of ocean waves at S-band to determine the properties of ocean wave imaging at this wavelength.

#### D. SAR ALTIMETRY

Since the SAR employs a short pulse to resolve range differences, it has the inherent capability of being operated as an altimeter if one of its lobes points directly to the nadir. The resolution of such a system depends upon the chirp bandwidth  $\Delta f$  employed and is equal to the range resolution capability  $2.8 c/\pi \Delta f$  for the SAR. For the Seasat SAR with a chirp bandwidth of 19 MHz, the range resolution capability is approximately 10 m. For a higher range resolution, a proportionately higher bandwidth needs to be employed and this may necessitate using a higher frequency SAR. Table III lists the different available devices for obtaining the higher bandwidths.

Some additional height information can be made available from the amplitude and phase jitter of a conventional radar. A large antenna can be used to transmit high frequency radiation and the spatial period of the amplitude jitter may be used to determine the satellite height. Cross-correlating the return signal from an imaged nadir point as a function of the frequency



variation in the chirp bandwidth would give the height variation within a resolution cell; however, to extract the absolute height of the spacecraft from this information may be quite difficult. The synthetic aperture radar may be used as a synthetic interferometer radar where either two radar systems spatially separated in height are employed or the bandwidth separated into two sections and the return from each radar combined interferometrically. By following the line of constant null, the height variations may be mapped. However, the accuracy and feasibility of such a system still need to be demonstrated and may not be any better than the resolution available from the standard operation of the SAR as an altimeter.

TABLE III

Chirp Pulse Generation for Altimetry

Device	Bandwidth MHz	Frequency f. MHz
Folded-Tape Meander Line	0.5 f	2000
Waveguide Operated Near Cutoff	0.2 f	5000
YIG Crystal	0.5 f	2000
Three Terminal GaAs Oscillator	0.02 f	60 to 2500 MHz
Voltage Tunable Magnetron	0.5 f	100 to 10,000 MHz
Backward Wave Oscillator	0.2 f	2 to 18 GHz

IV. RECOMMENDED SYSTEM STUDIES

Further hardware system studies are required to fully develop the concepts described and some of them are stated below. Checkerboard Radar: (Single beam) The availability and design of mechanical scanners, and their stability; also design of antenna for the electronic scanning, with cost, weight, reli-

ability, and volume estimates. An analysis of chirp bandwidth effects on frequency scanning and compensation if possible in the data processing. (Multibeam-Multifrequency) Transmitter-receiver system capable of handling the separate frequencies; design of antenna and performance analysis of multi-antenna system vs the frequency scanned antenna. (Multibeam-Multiangle) Design of the antenna to provide beams at multiple angles in azimuth and range. Receiver to separate the different Doppler centered returns for processing. Mechanical design constraints imposed on the data processor for each of the checkerboard radar configurations. Range ambiguity suppression for high look angles. Studies need to be made on the limitations imposed on the available spacecraft power, data handling capabilities and onboard processing. Forward and Backward Looking Radar: Analysis of optimum technique for demodulation of added Doppler component. Geometric correction for the distorted range and azimuth format for these modes for data interpretation.

S-band Radar System: Availability of a solid-state radar system, reliability of non-solid-state radar. Experimental validation that ocean waves are imaged at S-band. SAR Altimeter: High bandwidth capability for the SAR, and design of such a system.

## V. CONCLUSIONS

While the measurement functions derived for the SEASAT-FOLLOW-ON Missions can, in principle, be performed by the currently available technology, considerable further study is required to develop some of the instruments involved to obtain an understanding of their operation and the interpreta-

tion of their data. Some of these desired studies may be summarized as follows:

1. Development of further understanding of the image formation mechanisms of the Synthetic Aperture Imaging radar and the interpretation of these images. Direct information retrieval from the radar signal and hardware studies on the feasibility of operation of the radar as an altimeter or scatterometer.
2. Hardware and cost analysis for the checkerboard imaging radar so that data from high swaths required for global oceanography are possible.
3. Real-time, compact, opto-electronic data processing techniques for the Synthetic Aperture Radar and the use of lightweight, low-cost holographic elements in these systems.
4. Development of the microwave pressure sounder for surface pressure measurements.
5. Development of the atmospheric sounder. This would provide high resolution information on the atmospheric water vapor content, rain rate and particle velocities. Hardware studies for a combined scatterometer-atmospheric system.

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